Name: ______________________________
Date: ____ / ____ / ____ **Class Hour:** ____

SOLAR PV:
BATTERY STORAGE and CHARGE CONTROL

INTRODUCTION:

Rechargeable battery technologies are evolving, prices are falling, and more people are choosing to install batteries (or a battery—the terms will be used synonymously here). This is happening in a wider variety of solar PV situations than ever before. How do these batteries work?

Deep Cycle Batteries:

Despite differences in technology, all batteries used in the solar PV world are deep cycle batteries. These batteries are very different from the regular batteries you usually buy in a hardware or department store. Deep cycle batteries are capable of:

- being electrically recharged many times
- storing energy for long periods of time
- discharging most of their energy many times (***deep*** discharge over many charge ***cycles***)

Like any battery, deep cycle batteries store energy through a chemical reaction that develops electric potential and results in electricity.

Several general types of rechargeable solar PV batteries are currently in use. All of them are manufactured differently and have somewhat different characteristics:

- Flooded batteries are the most common type in use today and are similar to the standard lead-acid battery in your car.
- Gel batteries as you would expect have a chemical gel substance inside of them instead of a liquid.
- AGM (Absorbed Glass Mat) batteries are made with an acid which is suspended in a glass mat separator.
- In lithium-ion battery technology, lithium ions move to a positive electrode during electrical charging. The lithium ions move back to a negative electrode when electricity is used or discharged from the battery.

Regardless of the type installed, rechargeable batteries must be properly regulated for effective use.

Charge Controller:

A charge controller is a small device with solid state micro circuitry. It is placed between solar panels and batteries. Its purpose is to charge and discharge deep cycle batteries for efficient use and long life.

Protecting against damage and the permanent loss of storage capacity of a battery, a charge controller:

- Regulates the flow of electricity into a battery, preventing it from overcharging. Prolonged overcharging will permanently damage a deep cycle battery and can be dangerous to its owner.
- Regulates the flow of electricity out of a battery, preventing it from overdischarging. Depending on the type, if a deep cycle battery is discharged below 20-50% of its full charge capacity very often, it will fail.

A charge controller also prevents the backflow of electrical current from batteries into the solar array at night.

Take some time now to think like a charge controller by answering the questions in the table on the next page.

Q1. Using the letter choices (below), match the status of each device (left) to the probable response from the charge controller (right):

a. The charge controller supplies charge to the battery only

b. The charge controller supplies the load from the battery only.

c. The charge controller supplies the load from the PV modules only—provided the PV array is large enough to satisfy load requirements.

d. The charge controller supplies the load from both the battery and the PV modules.

e. The charge controller opens the circuit from the PV modules, preventing overcharging or overdischarging of the battery.

Table 1.0

Q.	Battery: 	Solar PV Modules: 	Load: 	Charge Controller Response: 
1a.	Discharged* (See ▼)	Full Sun Available	No Load	a
1b.	Discharged* (See ▼)	Full Sun Available	Electricity Needed	c
1c.	Fully Charged	Full Sun Available	Electricity Needed	d
1d.	Fully Charged	Full Sun Available	No Load	e
1e	Fully Charged	Half Sun Available	Electricity Needed	d
1f.	Fully Charged	No Sun; Nighttime	Electricity Needed	b
1g.	Discharged* (See ▼)	No Sun; Nighttime	Electricity Needed	e

* = Rechargeable, deep cycle batteries are never fully discharged. They are only discharged to a level that keeps them healthy and functional for the longest period of time.

In this lab exercise, you'll work with two of the most basic units in electricity, Volts and Amps. Though you won't work with Power in this lab, Volts and Amps enable us to calculate electric Power in Watts, according to Ohm's Law. This Ohm's Law explanation page is placed here to provide you with an explanation for Amps and Volts.

Ohm's Law is named after a German Physicist Georg Ohm. It's used everywhere and all of the time in the electrical industry. Ohm's Law states that:

The POWER, **P**, flowing through an electrical circuit is the product of the CURRENT, **I**, multiplied by the ELECTRIC POTENTIAL, **E**

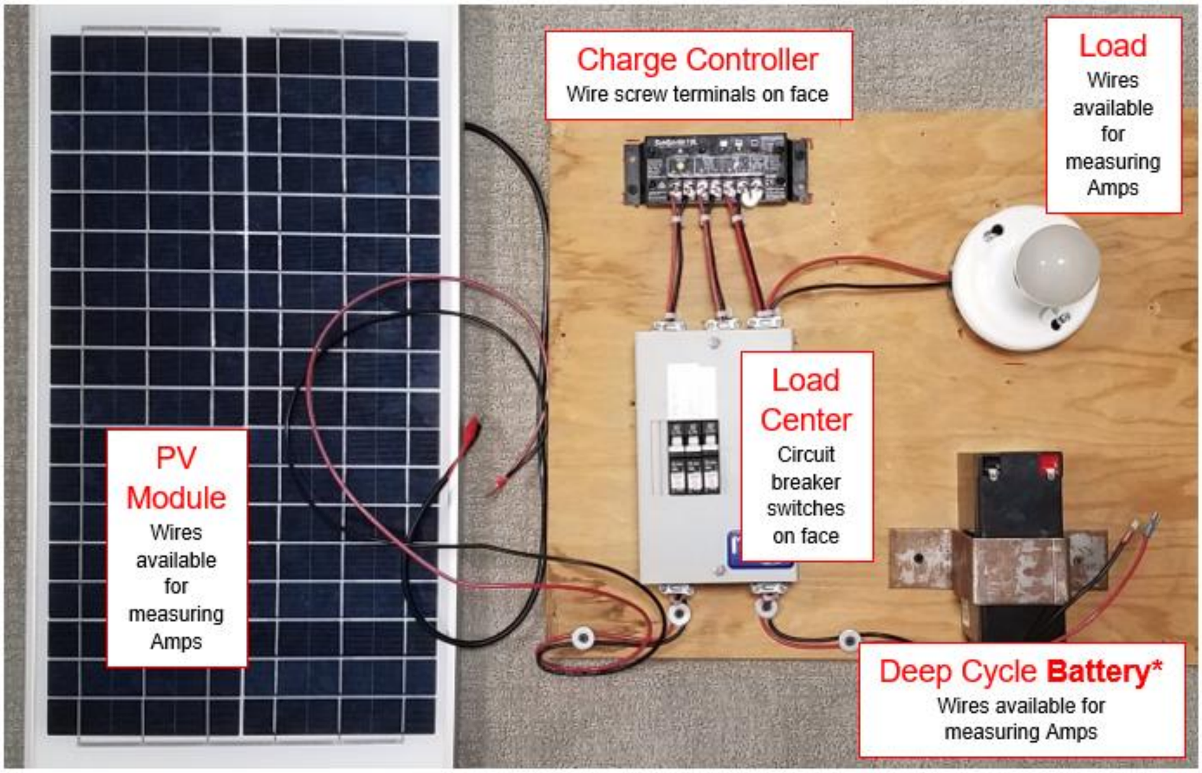
$$\boldsymbol{P = I\ x\ E}$$

This can be remembered as Power is "easy as PIE"

P is **POWER**	**I** is **CURRENT**	**E** is **ELECTRIC POTENTIAL**
It's measured in units of **Watts (W)** and power is sometimes referred to as wattage It is the rate at which work is done (and energy is used) in an electrical circuit $1\ Watt = \frac{Joule}{second}$ *Students may also recall from physics class that Power = Work / time*	It's measured in units of **Amps (A)** and current is sometimes referred to as amperage It is the rate at which electrons flow through an electrical circuit $1\ Amp = \frac{Coulomb}{second}$ *The symbol **I** comes from the French phrase "**i**ntensité de courant" (intensity of current).*	It's measured in units of **Volts (V)** and electric potential is sometimes referred to as voltage It is the amount of potential energy available to push electrons through an electrical circuit $1\ Volt = \frac{Joule}{Coulomb}$ *Electric potential in some older texts was referred to as **E**lectromotive Force (**E**MF). This is technically not correct, since electric potential is not a force.*

A historical note: Ohm's Law states that for a given resistance (R), the current in a circuit is given by I = E/R. It was James Prescott Joule, not Georg Simon Ohm, who first discovered the mathematical relationship between power dissipation and current in a circuit. Joule's discovery, published in 1841, is properly known as Joule's Law. However, the power equation is so commonly associated with the Ohm's Law equation relating voltage, current, and resistance (I=E/R) that it is frequently credited to Ohm.

MATERIALS:



*In this lab activity you'll use a deep cycle battery that is completely sealed for safety purposes. The battery's electric potential rating is *nominal* depending on its state of charge. Measured volts will be higher than rated when the battery is fully charged. Measured volts will be lower than rated when the battery is discharged.

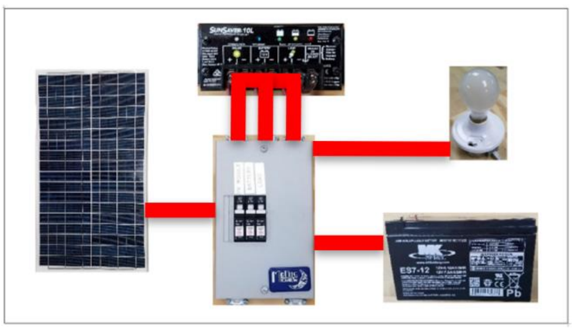
Now it's time for you to see how a deep cycle battery and charge controller function under normal operating conditions. In this lab you will:

- Predict, measure, and explain electric potential (volts) and current (amps) in a variety of dynamic settings.
- Understand the function of the charge controller in governing current flow in a renewable energy battery storage system

PROCEDURE:

This lab assumes you are outdoors, and your PV module is in full sun. As you begin the lab, you are plainly starting in sunny, daytime conditions.

1. Check to ensure all three circuit breakers at the load center are switched off. Switched off at the load center, the circuits from the PV module, the battery, and the load are all open circuits.



2. Connect the PV module to the wires from the load center. Then connect the battery to the wires from the load center.

3. Before you measure the electric potential on the battery:

Battery rated volts, or slightly higher or lower depending on battery state of charge. What do you expect this measurement to be?

4. Measure the electric potential *on the* *wires* from the battery in DC volts.

Actual measurement should be close to the battery rated volts. What is your actual measurement?

Q2. Before going further, explain how you knew what the actual measure would be (or how you could or should have known).

The battery's electric potential rating is *nominal* depending on its state of charge. Measured volts will be higher than rated when the battery is fully charged. Measured volts will be lower than rated when the battery is discharged. [See the Introduction to this lab, Materials section.]

5. Before you measure the electric potential on the PV module:

VOC on module. What do you expect this measurement to be?

6. Measure the electric potential *on the* *wires* from the PV module in DC volts.

VOC on module. What is your actual measurement?

Q3. Before going further, explain how you knew what the actual measure would be (or how you could or should have known).

Light is available to the module and we are in open circuit conditions. [See step 1].

7. Before you measure the electric potential on the load:

0 V What do you expect this this measurement to be?

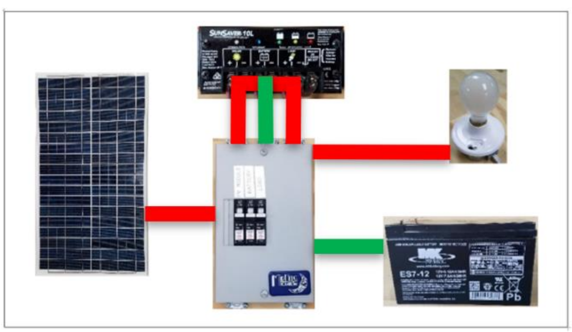
8. Measure the electric potential *on the* *terminals* of the charge controller from the load in DC volts.

0 V What is your actual measurement?

Q4. Before going further, explain how you knew what the actual measure would be (or how you could or should have known).

It is an open circuit to the load. No current or force is available to provide electric potential.

9. Turn on the switch for the battery at the load center. This completes the circuit from the battery to the charge controller.



10. Before you measure the electric potential on the battery:

Battery rated volts, or slightly higher or lower depending on battery state of charge. What do you expect this measurement to be?

11. Measure the electric potential *on the terminals* of the charge controller from the battery in DC volts.

Actual measurement should be close to the battery rated volts. What is your actual measurement?

Q5. Before going further, explain how you knew what the actual measure would be (or how you could or should have known).

The battery's electric potential rating is nominal depending on its state of charge. Measured volts will be higher than rated when the battery is fully charged. Measured volts will be lower than rated when the battery is discharged. [See the Introduction to this lab, Materials section.]

12. Before you measure the irradiance at the PV module surface:

≈ 500 - 1000 W / m2 In what general range do you expect this measurement to fall?

13. Measure the irradiance at the PV module surface with the pyranometer in watts/m^2.

Actual measurement. What is your actual measurement?

Q6. Before going further, explain how you knew what the actual measure would be (or how you could or should have known).

In good sun we should get ≈ 500 - 1000 W / m^2.

14. Before you measure the current from the PV module:

0 A What do you expect this measurement to be?

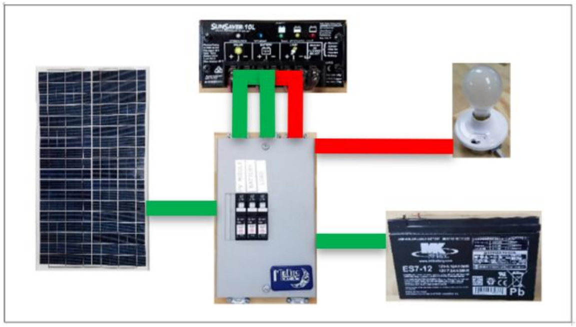
15. Place the clamp from the clamp-on multimeter around a wire from the PV module. Measure the current from the module in amps.

0 A What is your actual measurement?

Q7. Before going further, explain how you knew what the actual measure would be (or how you could or should have known).

The PV module is still an open circuit. No current can flow.

16. Turn on the switch for the PV module at the load center. This completes the circuit from the PV module to the charge controller. This also completes the circuit between the PV module and the battery through the charge controller. The charge controller is now actively managing the battery charge level.



17. **Actual measurement.** Now quickly measure the electric potential *on the terminals* of the charge controller from the battery in DC volts.

18. Before you measure the current from the PV module again:

[(Step 13 measured W / m^2) / (1000 W / m^2)] X IMP Assume your charge controller has the ability to continuously adjust the output of your module for maximum power. This is called maximum power point tracking (MPPT). Based on the irradiance you measured in step 13, what would you expect the current measurement from your PV module to be now?

19. **Actual measurement.** Place the clamp from the clamp-on multimeter around a wire from the PV module again. Measure the current from the module in amps.

Q8. Does your actual measurement match your prediction very well? If it does not, provide a good explanation for the difference.

Our charge controller doesn't have the ability to continuously adjust the output of our module for maximum power. For this reason, our expected measurement may or may not match our actual measurement very well. It has the best chance of matching pretty well if our conditions are full sun with no clouds. Irradiance under these conditions should be close to 1000 W / m2.

20. Before you measure the current from the battery:

Same as module current. What do you expect this measurement to be?

21. Place the clamp from the clamp-on multimeter around a wire from the battery. Measure the current from the battery in amps.

Same as module current. What is your actual measurement?

Q9. Why is current measured from the battery the same as the current measured from the PV module?

The circuit between the PV module and the battery through the charge controller is complete. The charge controller is now actively managing the battery charge level. The battery is being charged from the PV module. All current from the module is charging the battery.

22. **Actual measurement.** Measure the electric potential on the battery from the terminals of the charge controller in DC volts again.

Q10. **Higher.** Is this measurement higher or lower than the electric potential measurement you took on the battery from step 17?

Q11. Explain the difference in these measurements.

Electric current has begun to charge the battery. Current flowing into the battery increases it electric potential, so the battery volts measurement is higher.

23. Turn on the switch for the load at the load center. This completes the circuit from the load to the charge controller. All electrical circuits are now complete, and the charge controller is actively managing current flow throughout your whole system.

24. Complete the measurements indicated in the following table (**Table 2.**):

Table 2.

Example data: Device:	Electric potential in **Volts** (measured at the charge controller terminals)	Current in **Amps** (measured on the wires for each device)
Load	**11.8 V**	**2.1 A**
Battery	**11.8 V**	**1.2 A**
PV Module	**11.8 V**	**0.9 A**

Q12. Why did the electric potential of the battery (volts) change when compared with the measurement you took a step 22?

The battery is charged and available, and we've turned on a load. Current is drawn from the battery and the battery is discharged. The electric potential on the battery in volts drops in comparison to earlier measurements.

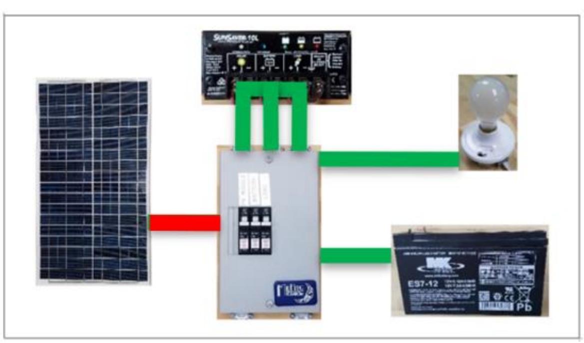
The battery determines the electric potential of the whole system when battery, module, and load circuits are all complete.

Q13. * Is the load getting power from the PV module, the battery, or both?

Q14. Explain how you know the answer to the previous question.

Current from both the battery and the PV module is supplying the load. The current from the battery and module add up to the current supplying the load.

25. Turn off the switch for the PV module at the load center. Doing this opens the circuit from the PV module to the charge controller, preventing the module from producing current. Even though your PV module is still in the sun, you are now essentially, simulating nighttime conditions.



26. Before completing the measurements indicated in the following table (**Table 3.**), what do you expect your measurements to be? Write them into **Table 3**.

27. Now complete **Table 3.** by writing your actual measurements into the table.

Table 3.

Example data: Device:	Electric potential in **Volts** (measured at the charge controller terminals): Expected	Electric potential in **Volts** (measured at the charge controller terminals): Actual	Current in **Amps** (measured on the wires for each device): Expected	Current in **Amps** (measured on the wires for each device): Actual
Load	**11.8V**	**11.8V**	**2.1V**	**2.1V**
Battery	**11.8V**	**11.8V**	**2.1V**	**2.1V**

Q15. Why is the current on the load wire the same as the current on the battery wire?

***The load is only being powered by current from the battery.**

SHOW WHAT YOU KNOW:

Q16 and Q17: Other answers are possible, and placement of answers may be different.

Q16. A solar PV system with batteries is considerably more expensive than a grid-tied system. The owner of grid-tied only system sells the electricity they produce to their utility and buys what they can't produce from the utility. No battery storage is needed.

Despite the added expense, provide three good reasons why many people still choose to install a solar PV system with battery storage.

Read what's written next to all three blanks before writing about any one of them.

16-1. Provide a reason that is primarily place or location dependent.

Live where connection to the grid is impossible, difficult, or very expensive.

16-2. Provide a reason that is situation dependent, and different than your answer above.

Utility price for electricity is high and reimbursement for electricity produced by homeowner system is low.

16-3. Provide a third reason that is different from either of your previous answers.

Own an electric vehicle.

Q17. Naturally a system without batteries will not need a charge controller. A PV system of this kind is almost always connected to the local electricity grid. A PV system without batteries that is connected to the local energy utility grid is said to be "grid-tied."

Provide two good and different reasons why many people choose a grid-tied PV system over one with battery storage.

17-1. **A PV system without batteries is much less expensive.**

17-2. **Battery storage systems require monitoring and maintenance.**

Q18. For the following, assume a linear discharge rate and a fully charged battery.

A deep cycle battery rated at 8 amp-hours will be fully discharged by a load of 2 amps in 4 hours. The math looks like this:

$$\frac{8\ \cancel{amp}\ hours}{2\ \cancel{amps}} = 4\ hours$$

However, deep cycle batteries should never be fully discharged. In general, if a deep cycle battery is discharged below 20-50% of its full charge capacity very often it will fail.

With this in mind, answer the following question.

You have a 12 watt LED lamp, rated at 0.1 amps. This lamp produces 800 lumens (~60 watt incandescent equivalent). You also have a 7.2 amp-hour, deep cycle rechargeable battery. To protect this battery, your charge controller will only permit the battery to discharge to 50% of its full charge capacity.

36 hours. How many hours will the battery power the lamp load? Once again, assume a linear discharge rate and a fully charged battery. Support your answer with the appropriate math, below.

Math work:

$$\frac{7.2\ \cancel{amp}\ hours}{0.1\ \cancel{amps}}\ X\ 0.50 = 36\ hours$$

Q19. Use Ohm's Law (explained earlier) to complete the table below. It's easy as **PIE**!

Table 4 [All of the measures in the tables were taken at 25.0 ºC and 1000 W/m^2.]

Educational / demonstration modules

Q	Number of cells on module	Volts / module cell	Module Electric Potential (Volts)	Module Current (Amps)	Module Power (Watts)
19a.	3	0.40 V	1.20 V	0.83 A	**1.00 W**
19b.	12	**0.50 V**	**6.00 V**	0.67 A	4.02 W

Residential / commercial modules

Q	Number of cells on module	Volts / module cell	Module Electric Potential (Volts)	Module Current (Amps)	Module Power (Watts)
19c.	48	0.47 V	22.6 V	8.90 A	**201.1 W**
19d.	**60**	0.48 V	**28.8 V**	8.34 A	240.2 W
19e.	72	**0.45 V**	32.4 V	**9.26 A**	300.0 W

Madison College Materials List For This Lab:

Batteries should be fully charged in preparation this lab.

Batteries should be slightly discharged just before students perform the lab.

- 12 Volt rechargeable battery [~$25]
  AGB (Absorbed Glass Mat), enclosed Lead/Acid
  7.2 Amp-Hour deep cycle solar

- Charge Controller [~$75]
  Morningstar Sun Saver 10L
  Rated 12 volts, up to 10 amps

- PV Module [~$100]
  Dasol DS-A18-30, 30 Watt module

- Load Center [~$50]
  4 circuit breaker openings available, of which we use 3

- 3 DC rated circuit breakers [~$10 each]
  Rated up to 250 volts, up to 10 amps

- Standard metal octagon electrical box

- Plastic keyless lamp holder

- 25 Watt, 12 Volt incandescent lamp [~$3]

- Clamp-on multimeter capable of measuring DC amps [~$150]

- Standard digital multimeter to measure DC volts [~$40]

- Pyranometer [~$170]
  Daystar

- Electrical wire, 8-10 feet
  Romex 14 AWG / 2 Conductors (cut bare ground off at open ends)
  Color white wire with permanent red marker at open ends

- Male and female wire spade connectors (appropriate crimping tool needed)

- 6 -1/2 inch Romex cable connectors

- Romex electrical wire staples

- 3/8 inch plywood board, roughly 18 inches X 24 inches